NASA PROJECT APOLLO WORKING PAPER NO. 1009

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PRELIMINARY INVESTIGATION OF GROUND TRACKING

AND COMMUNICATION SYSTEMS ADAPTABLE

FOR USE IN PROJECT APOLLO

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

SPACE TASK GROUP

Langley Field, Va.

January 31, 1961

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1.0 SUMMARY

The defined Apollo circumlunar mission requires a continuous spacecraft-ground link with the possible exception of the transit around the far side of the moon. The limitations of available and proposed ground systems indicate a necessity for a sequence of two tracking phases: earth proximity and deep space.

Microlock, Minitrack, and existing Mercury ground stations (with the proposed increased range Verlort radar) are adequate for earth proximity tracking and communication. Other usable systems for earth proximity tracking include the AZUSA Mark II and the Spacescan, but a number of stations, other than those presently planned, would have to be constructed to effectively use these systems.

The D.S.I.F. TRAC(E) system presents a minimum power tracking and communication system for deep space. The TRAC(E) depends on statistical methods for accuracy which corresponds to a position error of 50 nautical miles at lunar distances. Without this statistical method, the inherent system capability allows an error of 400 nautical miles. The Mistram presents the most accurate tracking system (approaching an estimated positional error of 5 nautical miles at lunar distances), but does not offer a desirable technique for telemetry. Other systems that could be used for deep space tracking include the Millstone and the highly accurate Haystack. In addition to beacon tracking, both the Millstone and Haystack systems are also well-suited to skin tracking, approaching 2,300 and 14,000 nautical miles, respectively, for a 1-meter^2 target.

Satellite relay stations could be deployed beyond the moon's shadow and used as a means of removing lunar blackout when the spacecraft encircles the far side of the moon.

2.0 INTRODUCTION

The purpose of this paper is to present basic descriptions and characteristics of several tracking systems suitable for use in connection with a Project Apollo-type vehicle. The information presented herein is intended to be used as a means of comparing the various essential characteristics of some systems that are currently available or will be available within the time schedule of Project Apollo. All computation has been based on optimum operating circumstances with no regard for circuit margin. Variation of such parameters as decreased receiver sensitivity due to side lobe ground reflection, hardware losses, true path loss as a function of antenna pointing angle at frequencies which present additional ionospheric losses, etc., must be considered in a final analysis. A list of references is presented in section 5.0 which gives more detail to the systems described herein.

3.0 EARTH PROXIMITY TRACKING AND COMMUNICATION

Earth proximity range is defined as that distance from the ground which extends to approximately 7,000 nautical miles from the surface of the earth.

The established networks of Microlock and/or Minitrack systems should be used since their sensitivities require a relatively small amount of spacecraft power. For a distance of 7,000 nautical miles, the required vehicle transmitted carrier power for the Microlock and Minitrack is 15 milliwatts and 200 milliwatts, respectively. Both systems have telemetry capability.

The following subsections describe briefly other systems which could augment the Microlock and Minitrack.

3.1 UHF Telemetry

3.1.1 Mission Application

Telemetry

3.1.2 System Description

Onboard transducers measuring such phenomena as heat, velocity, acceleration, EKG, etc., are used to modulate the vehicle transmitter and provide in-flight real-time data to the ground. The four predominantly used telemetry systems are: PDM/FM, FM/FM, PCM/FM, and PAM/FM.

PDM/FM (pulse-duration-modulation/frequency modulation) is used when a large amount of information channels can be time-shared. The output of each transducer is sampled by a commutator. The output of the commutator is applied to a keyer which converts the sampled signals from varying amplitude pulses to constant amplitude, variable width pulses. The variable width pulses are then applied to subcarrier oscillators which frequency-modulate the transmitter.

FM/FM (frequency modulation/frequency modulation) systems use the transducer outputs to frequency-modulate a subcarrier oscillator. Eighteen subcarriers can be used simultaneously to continuously monitor 18 variables. If additional information is required, one or more channels may time-share other subcarriers.

PCM/FM (pulse-code-modulation/frequency modulation) is a digital telemetry technique useful when high data rates and high accuracy are desired. A commutator samples the transducer voltages. The output of the commutator is applied to a coder which transforms the voltage samples into binary form. The R.F. carrier is then frequency shift-keyed by the coded pulses.

PAM/FM (pulse-amplitude-modulation/frequency modulation) systems use a commutator to sample the output of each transducer. The output of the commutator is a series of constant width, variable amplitude pulses which frequency-modulate a subcarrier oscillator. The subcarrier oscillator then frequency-modulates the transmitter.

3.1.3 Range and Limitations

Using a Mercury system consisting of a tri-helix antenna, an I.F. bandwidth of 100 kc, and an $\frac{S+N}{N}$ of 10 db, a vehicle transmitted power of 15.5 watts would afford a range of 7,000 nautical miles.

3.1.4 Geographic Location

Mercury stations and missile ranges.

3.1.5 Status

The telemetry subsystems described herein are presently available and can be utilized in the first phase of Apollo. A telemetry band change (and consequent system change) will be implemented around 1970..

3.1.6 System Characteristics

3.1.6.1 Ground Telemetry Antennas

7-Turn Helix

Gain	12 db (av.)
Beamwidth	45° conical (av.)
Polarization	Right circular
Frequency Band	215 to 260 mc

Quad-Helix

Gain	18 db (av.)
Beamwidth	18° conical (av.)
Polarization	Right or left circular
Frequency Band	215 to 260 mc

Tri-Helix

Gain	18 db (av.)
Beamwidth	20° conical (av.)
Polarization	Right circular
Frequency Band	215 to 260 mc

TLM - 18

Gain	28 db (av.)
Beamwidth	5° conical (8° when nutating)
Polarization	Right circular
Frequency Band	215 to 246 mc

3.1.6.2 Telemetry Receivers

Present capability includes the following systems:

PDM/FM

FM/FM

PCM/FM

PAM/FM

Variable Bandwidth Receiver

RF Frequency Range	216 to 260 mc
N.F.	8 db (max)
Video Bandwidth	1 kc - 1 mc (variable)

Fixed Bandwidth Receiver

RF Frequency Range	216 to 260 mc
N.F.	7 db (max.)
I.F. Bandwidth	500 kc and 100 kc (selectable)

Fixed Bandwidth Receiver (Mercury Net)

RF Frequency Range   216 to 260 mc

N.F.   8 db (max.)

I.F. Bandwidth   100 kc and 50 kc (selectable)

3.2 Spacescan

3.2.1 Mission Application

Tracking

3.2.2 System Description

This is a passive system providing spacecraft position, velocity, and trajectory. Two pair of scanners are placed orthogonal to each other on the ground. Each scanner provides a flat beam of $\frac{1}{2}^{\circ}$ in the scanning direction and 100° in the direction transverse to the scan. A simple triangulation method of measuring three angles is used. All scanners continually sweep predetermined sectors, affording instantaneous antenna angular information, station identity, and station location on the transmitted beam. The information is transmitted to the vehicle in the form of a pulse distance modulation. The spacecraft then computes its position, velocity, and trajectory. It may telemeter this information back to the ground station.

The system requires no ground data transmission network or central computation as compared to other multiple antenna systems.

3.2.3 Range and Limitation

A range of 7,000 nautical miles is attained if a vehicle receiver sensitivity of -71 dbm is used. Operating at KU band will minimize plasma sheath, ionosphere, and RFI problems but will present greater free space loss per distance travelled than normal deep space frequencies of 100 to 10,000 mc.

3.2.4 Geographic Location

None

3.2.5 Status

Proposal stage

3.2.6 System Characteristics

Ground antenna

Half-power beamwidth	$\frac{1}{2}^{\circ} \times 100^{\circ}$
Antenna Gain/Isotropic	41 db

Accuracy of angular information 0.01°

Ground Receiving System

None required

Ground Transmitting System

Frequency   13 and 16 kmc

Transmitter power   500 kw

Pulse spacing   16 to 96 μs

3.3 AZUSA Mark II

3.3.1 Mission Application

Tracking

3.3.2 System Description

This is a cw, phase comparison system measuring two direction cosines, two cosine rates, range, and coherent range. An interferometer method is used to obtain direction cosines and cosine rates. Range is determined by a phase delay of a ground-supplied frequency modulation which is retransmitted by the spacecraft transponder. Coherent carrier phase tracking provides highly accurate incremental range values.

The system has nine receiving antennas and one transmitting antenna.

3.3.3 Range and Limitation

For a range of 7,000 nautical miles, a vehicle antenna gain of 20 db, receiver sensitivity of -71 dbm and transmitter power of 8 watts could be used.

The AZUSA will not track a cross-polarized signal, i.e., if polarity changes by 90° during flight, complete loss of signal occurs. The polarization of the ground antennas is adjusted for an optimum, dependent on the expected spacecraft antenna pattern. Nulls in excess of 10 db greatly reduce the system's capability and could result in complete loss of track.

3.3.4 Geographic Location

Cape Canaveral, Florida

3.3.5 Status

Operational

3.3.6 System Characteristics

Ground Antenna

Antenna Gain/Isotropic	35 db
Accuracy	Direction cosine: ± 10 parts/10^6 rms
	Range: ± 10 ft + 5 parts/10^6 rms
Tracking Rate	30,000 ft/sec in range
	0.1 cos/sec in angle

Ground Receiving System

Signal required at receiving antenna	-130 dbm
Frequency	5,000 $\pm$ 0.75 mc

Ground Transmitting System

Frequency	5,060 $\pm$ 0.75 mc
Transmitter power	2 kw

3.4 AN/FPS-16

3.4.1 Mission Application

Tracking

3.4.2 System Description

This is a C-band pulse radar providing real-time slant range, azimuth and elevation angles. The system can be used for skin tracking or with a beacon for extended range.

3.4.3 Range and Limitations

The present AN/FPS-16 can skin track a $1m^2$ vehicle to 131 nautical miles. A vehicle transmitted power of 155 watts and transponder receiver sensitivity of -65 dbm would allow automatic tracking to 7,000 nautical miles if the three megawatt modification kit were used.

3.4.4 Geographic Location

Mercury stations and missile ranges.

3.4.5 Status

Modification kits increasing the tunable transmitter power to 3 megawatts are available. Present plans consist of modifying the AN/FPS-16 systems at the missile ranges to afford a transmitter power of 5 megawatts.

3.4.6 System Characteristics

Since there are many versions of this radar in the field, nominal characteristics will be presented.

Ground Antenna

Half power beamwidth	1.1°
Antenna Gain/Isotropic	4 .5 db
Pointing accuracy	0.1 mil rms

Tracking rate

    Range   8,000 yds/sec

    Azimuth 40°/sec

    Elevation 30°/sec

Ground Receiving System

Frequency   5,400-5,900 mc (tunable)

Minimum discernible signal   -100 dbm

Signal required for automatic
range tracking   , -93 dbm

Ground Transmitting System

Frequency   Fixed: 5,480 ± 30 mc

                                       Tunable: 5,400-5,900 mc

Transmitter power (peak)   1 Mw (fixed)

Transmitter power (peak)   250 kw (tunable)

Pulse widths   0.25, 0.5, 1.0 µs

PRF   285, 341, 366, 394, 467,
569, 682, 732, 853, 1,024,
1,280, 1,364, 1,707

3.5   Mod II Verlort

3.5.1   Mission Application

Tracking

3.5.2   System Description

This is an extended range SCR-584. The system is a pulse type, measuring azimuth and elevation angles, slant range, altitude, and x-y ground position. The system can be used for skin tracking or with a beacon for extended range.

3.5.3   Range and Limitations

The present Mod II Verlort can skin track a $1m^2$ vehicle to 60 nautical miles. A vehicle transmitted power of 125 watts would be sufficient for the present ground station to receive spacecraft replies at 7,000 nautical miles but an increased power for the Verlort transmitting system is required to interrogate a Mercury-type transponder.

3.5.4   Geographic Location

Bermuda
Northwest Africa
West Australia
Hawaii
Southern California
West Mexico
South Texas

3.5.5   Status

A program to modify the Verlort system to afford a transmitter power of 5 megawatts and an increased antenna gain of 52 db has been undertaken.

3.5.6   System Characteristics

Ground Antenna

Half power beamwidth	2.5°
Antenna Gain/Isotropic	34 db

Pointing accuracy	1.0 mil
Tracking rate	50°/sec

Ground Receiving System

Frequency	2,700 - 2,950 mc (tunable)
Minimum discernible signal	-103 dbm
Signal required for automatic tracking	-98 dbm

Ground Transmitting System

Frequency	2,700 - 2,900 mc (tunable)
Transmitter power (peak)	250 kw
PRF	410, 512, and 584 pps

4.0 DEEP SPACE TRACKING AND COMMUNICATION

The Deep Space region is defined as that domain beyond 7,000 nautical miles of the earth's surface. At this point and beyond in space, three properly positioned stations located $120°$ apart on the earth would be sufficient to insure continuous acquisition of the spacecraft.

4.1 TRAC(E)

4.1.1 Mission Application

Tracking and Telemetry

4.1.2 This is a Doppler tracking system which measures two angles, radial velocity and range. TRAC(E) provides three channels of telemetry (AM/FM), a command link, and a UHF transmitter for ground to spacecraft communication. Extreme tracking sensitivities are realized in this system due to its usage of a very narrow bandwidth made possible by phase-locking techniques. The received signal is passed through a filter too narrow to pass the modulation frequencies, thus permitting only the average carrier frequency to be tracked. The modulation frequencies are passed through wider filters to present the raw telemetry data.

A mobile station is used near the launch site to provide telemetry, command, and tracking of the spacecraft from injection to about 10,000 miles altitude.

4.1.3 Range and Limitation

TRAC(E) can track to lunar distances if a carrier power of 100 milliwatts is radiated from the spacecraft.

Although the acquisition accuracy is listed as $0.1°$, a better resolution is obtained by the programed use of minimizing the sums of the squares of the observation error (statistical "least squares" method). Computed absolute spacecraft position approaches a tolerance of 50 nautical miles at lunar distances.

4.1.4 Geographic Location

Cape Canaveral
Goldstone
Puerto Rico (mobile)

4.1.5 Status

In its present configuration, TRAC(E) measures a one-way Doppler shift and thus depends on spacecraft oscillator stability for accuracy. Future site locations will include Johannesburg, South Africa and Woomera, Australia for full deep space tracking capability. An additional mobile station is planned for operational use in 1963.

Future modifications to the TRAC(E) include a two-way Doppler measurement (1961), and a ranging system using a 2115/2295 mc transponder (March 1963).

4.1.6 Present System Characteristics

Ground Antenna (85-foot)

Half power beamwidth	0.8°
Antenna Gain/Isotropic	41.1 db
Acquisition accuracy	0.1°
Tracking rate	1°/sec (max.)

Ground Antenna (10-foot, mobile)

Half power beamwidth	9.0°
Antenna Gain/Isotropic	22 db
Acquisition accuracy	0.05°
Tracking rate	10°/sec (max.)

Ground Receiving System

Frequency	955 to 965 mc (adjustable)
Tracking bandwidth	20 cps and 60 cps (selectable)
Telemetry bandwidth	0-3.5 kc
Noise figure	7.5 db (max.)

Ground Transmitting System (For use with 85-foot antenna)

Frequency	890 mc and 960 mc
Transmitter power	10 kw

Ground Transmitting System (For use with 10-foot mobile antenna)

Frequency	890 mc
Transmitter power	25 watts

4.1.7 Proposed System Characteristics

Ground Antenna (85-foot) (Aug. 1962)

Half power beamwidth	0.4°
Antenna Gain/Isotropic	51 db
Frequency	2295/2115 mc

Ground Antenna (10-foot, mobile) (Jan. 1963)

Half power beamwidth	3.0°
Antenna Gain/Isotropic	32 db
Frequency	2295/2115 mc

Ground Antenna (200-300 ft) (Dec. 1964)

Half power beamwidth	0.13°
Antenna Gain/Isotropic	62 db
Frequency	2295/2115 mc

Ground Receiving System (Aug. 1962)

Frequency	2295 ± 5 mc
Tracking bandwidth	3-250 cps
Telemetry bandwidth	0-1 mc

Ground Transmitting System (For use with 85-ft antenna)

Frequency	2115 ± 5 mc
Transmitter power	10 kw (July 1962) 100 kw (1963)

Ground Transmitting System (For use with 10-ft mobile
   antenna)

Frequency   2115 ± 5 mc

Transmitter power   25-200 watts (presently
                                   undetermined)

4.2 Mistram

4.2.1 Mission Application

Tracking and telemetry

4.2.2 System Description

This is a long baseline interferometer system, measuring range and range-rate. Mistram uses five linearly polarized antennas whose feed systems may be rotated. The Mistram tracks the spacecraft polarization vector and positions the feeds for a maximum received signal throughout the flight. Two ground carriers are transmitted to the transponder in the vehicle. One carrier is kept at a fixed frequency stabilized on the order of one part in 10^8 (long term). The other is a signal which is swept in frequency to provide a calibration of unambiguous range.

The transponder used is composed of a klystron which is locked to each signal from the ground. The transponder then provides a coherent offset and retransmits the signal to the earth.

In order to provide telemetry and command on the tracking carrier, the information would have to be phase-modulated on a subcarrier which in turn would have to be amplitude-modulated on the carrier.

4.2.3 Range and Limitations

In its present design stage, Mistram would afford tracking capability to the moon with a positional accuracy of 5 nautical miles if a 14-inch parabolic dish were used on the spacecraft and properly positioned toward the earth.

Improved transponder design for deep space application has not been considered to date, as the system was designed for AFMTC. Present transponder requires 95 watts of primary power and has a heat dissipation of 40 watts per square foot. The unit weighs 15 pounds.

The technique of amplitude-modulating a klystron to provide telemetry on the tracking carrier is not desirable and is difficult to accomplish satisfactorily. A separate carrier should be used for telemetry in this system and phase-modulation or frequency-modulation methods employed.

4.2.4 Geographic Location

Cape Canaveral, Florida

4.2.5 Status

The present Mistram project will be completed in May 1962.

4.2.6 System Characteristics

Ground Antenna

Half power beamwidth	1.8°
Antenna Gain/Isotropic	40 db
Acquisition accuracy (lunar distances)	0.001°

Ground Receiving System

Frequency	78 to 83 kmc
Minimum discernible signal	-140 dbm

Ground Transmitting System

Frequency (range)	8148 mc
Frequency (calibration)	7884 to 7892 mc (swept)
Transmitter power (2)	500 watts

4.3 Haystack

4.3.1 Mission Application

Tracking

4.3.2 System Description

This is a pulse radio-communication system which could be modified to a very long range and angle tracking radar. A steerable parabolic antenna of 120 feet is planned.

4.3.3 Range and Limitation

Haystack can skin track a $1m^2$ target to 14,000 nautical miles. A vehicle transmitted power of 70 milliwatts would allow the Haystack to beacon-track a spacecraft to the moon.

4.3.4 Geographic Location

Massachusetts

4.3.5 Status

Development stage

4.3.6 System Characteristics

Ground Antenna

Half power beamwidth	0.07^o
Antenna Gain/Isotropic	67 db
Pointing accuracy	0.005^o any position

Ground Receiving System

Minimum discernible signal	-154 dbm

Ground Transmitting System

Frequency	8 kmc
Transmitted power (av.)	100 kw
Pulse length	Presently undetermined
PRF	Presently undetermined

4.4 Millstone

4.4.1 Mission Application

Tracking

4.4.2 System Description

This is a pulse coherent Doppler system which provides real-time coded range, velocity, and angular rate. The system uses an 84-foot parabolic dish which is steerable in elevation and range. A conical lobing scan is used.

4.4.3 Range and Limitations

Millstone can skin track a lm^2 target to 2,300 nautical miles. A vehicle transmitted power of 400 milliwatts would allow the Millstone to beacon-track a spacecraft to the moon.

4.4.4 Geographic Location

Millstone, Massachusetts

Prince Albert, Saskatchewan

4.4.5 Status

Operational

4.4.6 System Characteristics

Ground Antenna

Half power beamwidth	2.1°
Antenna Gain/Isotropic	37 db
Pointing accuracy	0.15° each axis

Ground Receiving System

Minimum discernible signal	-145 dbm

Ground Transmitting System

Frequency	400 - 450 mc (adjustable)
Transmitter power (peak)	2.5 Mw (max.)
Pulse length	2.0 ms
PRF	30 pps

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